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Assignment #2
ME 444

1. Electric vehicles are on the rise, and more and more people are buying them. According to the EIA under the “Global EV Outlook of 2017” article, the number of battery electric cars sold in the US are shown in Figure 1.

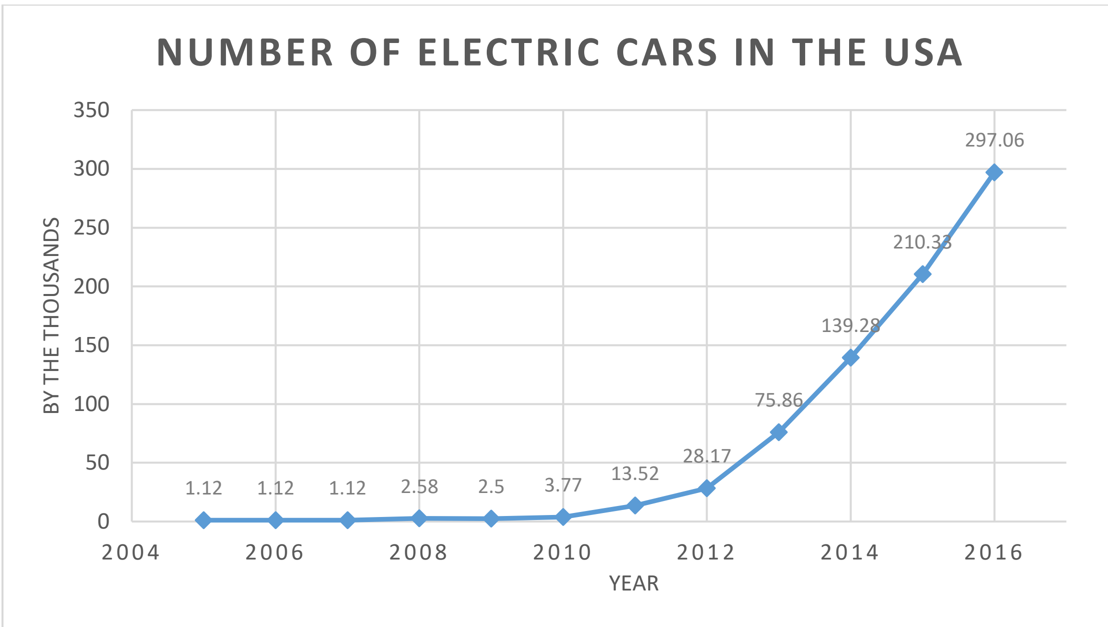

Figure 1: Total Electric Cars in the US

Although electric vehicles are certainly new to the market and may be emission-free from the tailpipe of the car, the electricity the vehicle consumes is most definitely not emission-free. To find out if an electric vehicle truly does produce less emissions than a gasoline vehicle, more research must be done on the emissions of power plants.

2. There are nine main sources of power: coal, natural gas, oil, nuclear, biomass, geothermal, solar, wind, and hydro. For simplicity, coal is generalized to bituminous coal, and petroleum is generalized to be diesel/heavy oil. For each source of energy, the amount of kg of CO2, NOx, and SOx produced per kWh of electricity generated is the table below. Due to limited data (found by a Stanford University article), only CO2 involves the lifecycle emissions. In other words, indirect emissions such as when mining or transporting the fuel are included for CO2. The numbers for NOx and SOx only involve the direct burning of the fuel.

Table 1: Emissions of Every Power Source, in kg/kWh

	CO_2	NO_X	SO_X
COAL	1.003	0.000885	0.001200
OIL	0.789	0.002655	0.001800
NATURAL GAS	0.522	0.003186	0.002703
BIOMASS	0.049	~0	~0
SOLAR	0.044	~0	~0
NUCLEAR	0.039	~0	~0
GEOTHERMAL	0.038	~0	~0
WIND	0.011	~0	~0
HYDRO	0.011	~0	~0

Unfortunately, I was not able to find NOx and SOx displayed in Table 1 in the internet. However, the sources that are non-conventional fossil fuels (biomass, solar, nuclear, etc.) are found to have low CO2 emissions, and are close to zero. CO2 emissions are generally higher than NOx and SOx emissions, so it can be inferred that the non-conventional fossil fuels have negligible NOx and SOx emissions. However, to get the emissions for fossil fuels, I had to use math and conversions using the following assumptions:

1. Baghouses and other means of reducing particulate matter are only used in coal power plants, and specifically reduce NOx and SOx emissions by 50%.
2. Bituminous coal is composed of 78% C, 5% H, 1% O, 5% N, 10% ash, and 1% S. Its higher heating value is 30 MJ/kg.
3. Oil is composed of 85% C, 12% H, 1% O, 1% N, and 1% S. Its higher heating value is 40 MJ/kg.
4. Natural gas is composed of 80% CH_4, 3% N_2, 4% CO_2, 2% H_2S, and 11% miscellaneous hydrocarbons. Its higher heating value is 50 MJ/kg.

Using these assumptions, I can calculate the SOx and CO2 emissions for coal, oil, and natural gas. An example calculation for the NOx value of coal can be seen below. Note that the equation is multiplied by 0.5 because of assumption (1).

$$\left(\frac{41.3\ kg\ NO_x}{14\ kg\ N}\right)\left(\frac{0.05\ kg\ N}{1\ kg\ coal}\right)\left(\frac{1\ kg\ coal}{30\ MJ}\right)\left(\frac{1\ MJ}{1000\ kJ}\right)\left(\frac{1\ kJ}{1\ kW\cdot s}\right)\left(\frac{3600\ s}{1\ hr}\right)\times\ 0.5 = 0.00885\ \frac{kg\ NO_x}{kWh}$$

3. Using information from the EIA, the total energy consumption of the nine sources of power in Iowa and Illinois are shown in the table below. The data is in GWh, and is from 2015.

Table 2: Energy Consumption in GWh

	IOWA	ILLINOIS
COAL	29,811	73,774
OIL	110	56
NATURAL GAS	2,398	10,864
BIOMASS	258	527
SOLAR	N/A	49
NUCLEAR	5,243	97,282
GEOTHERMAL	N/A	N/A
WIND	17,873	10,747
HYDRO	960	124

4. Table 1 is in $kg_{emission}$/kWh and Table 2 is in GWh. After converting Table 2 to kWh, both tables can be multiplied together to get the kg of emissions for both Iowa and Illinois. This is found in Table 3 below.

Table 3: Emissions of Iowa and Illinois in Kilograms

	CO_2		**NO_X**		**SO_X**	
	IA	**IL**	**IA**	**IL**	**IA**	**IL**
COAL	29900433000	73995322000	26382735	65289990	35773200	88528800
OIL	86790000	44184000	292050	148680	198000	100800
NATURAL GAS	1251756000	5671008000	7640028	34612704	6481794	29365392
BIOMASS	12642000	25823000	0	0	0	0
SOLAR	0	2156000	0	0	0	0
NUCLEAR	204477000	3793998000	0	0	0	0
GEOTHERMAL	0	0	0	0	0	0
WIND	196603000	118217000	0	0	0	0
HYDRO	10560000	1364000	0	0	0	0

Taking the sums of the value produces the following table with converted units:

Table 4: Emission Sum of Iowa and Illinois

	CO_2 (1000 METRIC TONS)	**NO_X** (SHORT TONS)	**SO_X** (SHORT TONS)
IOWA	31,663	37,826	46,796
ILLINOIS	83,652	110,288	130,067

Because the conventional fossil fuels contribute to much of the data, Table 5 is produced:

Table 5: Emission Sum by Fossil Fuels

	CO_2 (1000 METRIC TONS)		NO_X (SHORT TONS)		SO_X (SHORT TONS)	
	IA	IL	IA	IL	IA	IL
COAL	29,900	73,995	29,082	71,970	39,433	97,586
OIL	87	44	322	164	218	111
NATURAL GAS	1,252	5,671	8,422	38,154	7,145	32,370
ALL OTHERS	424	3,942	0	0	0	0

5. With all the numbers calculated, the data can be compared to a nominal source for verification of accuracy. Taken directly from the EIA, the emission sum of Iowa and Illinois's 2015 consumption is the following table:

Table 6: Nominal Value of Emission Sum

	CO_2 (1000 METRIC TONS)	NO_X (SHORT TONS)	SO_X (SHORT TONS)
IOWA	35,043	33,754	47,955
ILLINOIS	84,275	46,260	152,825

Comparing Table 4 and 6 together, it can be seen that the values are very close, with the exception of NOx in Illinois. For quantify the accuracy, the percent errors are calculated and shown in Table 6 below.

Table 6: Percent Error of Emission Sum

	CO_2	NO_X	SO_X
IOWA	9.64 %	12.06 %	2.42 %
ILLINOIS	0.74 %	100+ %	14.89 %

Although comparing the sums to the nominal values are insightful, it is not as insightful as comparing it by specific categories. Specifically, it is more helpful to look at the emissions by fossil fuels, similar to Table 5. To compare that data, nominal values are noted in Table 6:

Table 6: Nominal Value of Emission Sum by Fossil Fuel

	CO_2 (1000 METRIC TONS)		NO_X (SHORT TONS)		SO_X (SHORT TONS)	
	IA	IL	IA	IL	IA	IL
COAL	33,593	78,889	30,073	38,215	45,237	152,731
OIL	255	46	356	95	2,702	42
NATURAL GAS	1,185	5,332	1,051	3,186	11	21
OTHER	10	9	2,274	4,764	5	31

It can be observed that the results are strikingly different than the last comparison. To put the numbers into perspective, percent errors were computed in Table 6:

Table 6: Percent Error of Emission Sum by Fossil Fuels

	CO_2 (1000 METRIC TONS)		**NO_X** (SHORT TONS)		**SO_X** (SHORT TONS)	
	IA	**IL**	**IA**	**IL**	**IA**	**IL**
COAL	10.99 %	6.20 %	3.30 %	88.33 %	12.83 %	36.11 %
OIL	65.96 %	3.95 %	9.57 %	72.52 %	91.92 %	100% +
NATURAL GAS	5.63 %	6.36 %	100+ %	100+ %	100% +	100% +
OTHER	100+ %	100+ %	100+ %	100+ %	100+ %	100% +

Out of the 24 cells of data, 16 fall out of the error range: 10 are over 100%, and 6 are over 25% but less than 100%. Although this seems like a failed attempt, there are explanations to this:

- **"Other" is not clearly defined by the EIA**. It was not clear if it was referencing to unconventional fossil fuels (i.e. nuclear, shale oil, etc.) or if it was an umbrella term for "everything else," which is what this report assumed.
- **Due to trouble finding recent data, this report neglected NOx and SOx for non-conventional fossil fuels**. The EIA did not, and also included life-cycle analysis instead of emissions from burning fuel.
- **I assumed a constant chemical composition.** This is a very broad assumption, as this assumes that every power plant is buying the *same* type of fuel at the *same* chemical composition every time. Realistically speaking, there is heavy variance between the type of fuel used (i.e. bituminous vs sub-bituminous coal) as well as its chemical composition. Coal, oil, and natural gas is composed of C, H, O, N, and S, but it does not have just "one" composition since it depends on the reserve and location. For example, the NOx emission in Iowa is within the accepted range, but it is out of the range for Illinois. This could be due to variance of the oil; Iowa and Illinois most likely do not use the same petroleum chemical composition for their power plants.
- **My assumed nitrogen and sulfur percentages for natural gas is incorrect**, which is why the NOx and SOx percent error are over 100% across the board. Unlike coal and oil, finding the chemical composition was more difficult. I was not able to find individual element percentages, but instead found the composition by other hydrocarbons. However, I was able to find N_2 and H_2S, and used those numbers for my calculations. **Using N_2 and H_2S for NOx and SOx is another broad assumption.** NOx and SOx are the result of incomplete combustion, so the two are not greatly related. As a result, my NOx and SOx emissions are much higher than the nominal value.

  There are two main problems at hand here: too much variance within fuel/state/plants, and incorrect assumptions. To refine my results some more, I found a report from the USDE that outlines the mass per energy consumption of NOx and SOx, but it is from 2011. For the sake of comparison, an updated Table 1 using this information is below:

Table 7: Emissions of Every Power Source, in kg/kWh, with NOx/SOx using 2011 Data

	CO_2	NO_X	SO_X
COAL	1.003	0.000948	0.002386
OIL	0.789	0.002867	0.0024356
NATURAL GAS	0.522	0.0001678	0.000004536
BIOMASS	0.049	0.000372	0.00008165
SOLAR	0.044	0.000003629	0.000002722
NUCLEAR	0.039	0.000003629	0.000002722
GEOTHERMAL	0.038	0.000003629	0.000002722
WIND	0.011	0.000003629	0.000002722
HYDRO	0.011	0.000003629	0.000002722

With these numbers, new percent error can be calculated, as shown in Tables 8 and 9.

Table 8: Percent Error of Emission Sum, with NOx/SOx using 2011 Data

	CO_2	NO_X	SO_X
IOWA	9.64 %	4.77 %	64.34 %
ILLINOIS	0.74 %	72.78 %	27.34 %

Table 9: Percent Error of Emission Sum by Fossil Fuels, with NOx/SOx using 2011 Data

	CO_2 (1000 METRIC TONS)		NO_X (SHORT TONS)		SO_X (SHORT TONS)	
	IA	**IL**	**IA**	**IL**	**IA**	**IL**
COAL	10.99 %	6.20 %	3.59 %	100+ %	73.32 %	27.04 %
OIL	65.96 %	3.95 %	2.35 %	86.29 %	89.07 %	100+ %
NATURAL GAS	5.63 %	6.36 %	57.80 %	36.93 %	9.00 %	100+ %
OTHER	100+ %	100+ %	91.11 %	86.38 %	100+ %	100+ %

Although these Table 7 was taken from real data rather than assumptions, the results are not really any better than what they were before. Still, 16 out of the 24 cells are within the accepted error range (<25%), but there are less that are over 100%. One obvious reason the data gives inaccurate results is that the numbers were taken in 2011, and since more power plants have gotten more efficient over the last 6-7 years, the emission rate is no longer truly accurate.

To demonstrate the effect of the variance between fuels and states, the nominal value of the mass of emission per kWh of each type of fuel and emission is produced. This is done by dividing Table 6 with Table 2 in base units. The resulting Table 10 is shown below.

Table 10: Nominal kg/kWh Emission Values of Each State and Fuel

	CO_2		NO_X		SO_X	
	IA	**IL**	**IA**	**IL**	**IA**	**IL**
COAL	1.12687	1.06933	0.0009152	0.0004699	0.0013766	0.0018781
OIL	2.31818	0.82143	0.0029360	0.0015390	0.0222838	0.0006804
NATURAL GAS	0.49416	0.49080	0.0003976	0.0002660	0.0000042	0.0000018
OTHER	0.00041	0.00008	0.0000848	0.0000397	0.0000002	0.0000003

6. Using the nominal values, the question can be answered: does it make sense to drive an electric vehicle *today* in Iowa or Illinois? To begin the analysis, an electric vehicle must be picked. I've chosen the 2017 Tesla Model S for this report.

7. The 2017 Tesla Model S has a rated 104 MPGe of combined city and highway, which is the equivalent of 32 kWh/100 miles, or 0.32 kWh/mile. Using this specification, if the driver drives 15,000 miles per year, then the car used 4,800 kWh of electricity. Knowing the annual consumption of the car, the total emissions can be calculated by multiplying 4800 by the values in Table 10. This is seen in Table 11.

Table 10: Tesla Model S Emissions in Kilograms

	CO_2		NO_X		SO_X	
	IA	**IL**	**IA**	**IL**	**IA**	**IL**
COAL	5,409	5,133	4.393	2.256	6.608	9.015
OIL	11,127	3,943	14.09	7.387	107	3.266
NATURAL GAS	2,372	2,356	1.908	1.277	0.020	0.0084
OTHER	1.973	0.397	0.407	0.191	0.0009	0.0012

There is a stark difference of emissions between coal, oil, and everything else. However, to truly answer the question of whether al electric vehicle is worth environmentally worth it, a comparison must be made by a similar car using gasoline.

8. The similar gasoline car I chose was the 2017 Chevrolet Cruze, which has the rated laboratory testing condition of 36.2 mpg. I found the emission rates on the Next Green Car website, which is a site dedicated to guiding people to find low emission cars with statistics. Using the data on the Chevrolet Cruze, I was able to find that the car emits about 0.405 kg CO2/mile and 0.000312 kg NOx/mile on a life-cycle basis, which includes the emissions from the manufacturing of the car. Table 11 shows the total emissions per year if the Cruze is driven for 15,000 miles per year.

Table 11: Chevrolet Cruze Emissions in Kilograms

	CO_2	NO_X	SO_X
CHEVY CRUZE	6,075	4.68	~0

Although vehicles do emit SOx, the numbers are very small. For the sake of this report, the number is assumed to be negligible or very close to zero.

Finally, the question can be answered: does it environmentally make sense to buy an electric vehicle now? To answer this question, the Cruze and Model S are compared in Table 12. "Less" means that the Model S produces less emissions than the Cruze, and "more" means that the Model S produces more emissions than the Cruze.

Table 12: Comparing Emissions of the Cruze with the Model S

	CO_2		NO_X		SO_X	
	IA	**IL**	**IA**	**IL**	**IA**	**IL**
COAL	LESS	LESS	MORE	LESS	MORE	MORE
OIL	MORE	LESS	MORE	MORE	MORE	MORE
NATURAL GAS	LESS	LESS	LESS	LESS	EQUAL	EQUAL
OTHER	LESS	LESS	LESS	LESS	EQUAL	EQUAL

With the exception of CO2 in Illinois, using an electric vehicle with electricity from an oil power plant corresponds to *more* emissions produced than if using a similar gasoline vehicle. However, A coal power plant powering electric vehicles will result in less CO2 and NOx, but will result in more SOx. Even so, the magnitudes are not too different from each other; environmentally speaking, it would not make a huge change to drive one car over the other.

However, it is *definitely* worth the environment investment of an electric car if the powerplant uses natural gas or other types of fuels (i.e. nuclear or renewables). Much less CO2 and NOx would be produced, and the level of SOx would be about unchanged.

In summary, this report can be concluded as followed:

- If electricity comes from an oil power plant, it *does not* environmentally make sense to drive an electric vehicle in Iowa and Illinois. However, it is better to drive an electric vehicle in Illinois than in Iowa.
- If electricity comes from a coal power plant, it *does* environmentally make sense to drive an electric vehicle, but the difference is *not* that much better in Iowa and Illinois.
- If the electricity comes from a natural gas or other type of power plant, it *does* environmentally makes sense to drive an electric vehicle in Iowa and Illinois.